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PHOTOELECTRONIC AMPLIFIER WITH AN ANTIMONY-CESIUM CATHODE (MULTIPLIER PHOTOTUBE)

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[Figures referred to herein are appended.]

Introduction

When solving a number of problems in various fields of science and technology, difficulties often arise in choosing a method for measuring feeble light fluxes. Thus, for instance, in many problems of atmospheric optics, a very complicated method is employed in photometric analysis of very weak light intensities (1,2).

There are other well-known methods based on measuring light intensity by means of electrometers or through the amplification of photocurrents by means of vacuum tubes. Practice shows that, because of their complexity, these methods cannot be based upon widely used simple photometric apparatus adapted for daily use.

The principle of multiple amplification by means of secondary-electron emission has as its basis the construction of highly sensitive multiplier instruments such as the combination of photoelectrically active cathodes with effective emitters, whose action amounts to amplifying the cathode photocurrent. The positive results obtained recently (3,4,5) in employing photoelectron multipliers in spectrum analysis and astronomy attracted the attention of many research workers, and greatly revived the interest in photoelectron multipliers.

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In the multistage secondary-electron multiplier in a glass envelope and electromagnetic focusing suggested by Kubetskiy, a complicated Ag-O-Cs-layer was employed as a cathode, and a Cu-S-Cs-layer as an emitter in cascades. These layers were unresponsive to temperature changes and were efficient in respect to secondary-electron emission. In this type of multiplier (with 13 stages) with a total applied voltage of 750, an amplification of 10^5 is obtained, which provides spectrosensitivity of 1-3 A/lm (amperes/lumens).

The dark current of multipliers with given parameters varies from one type to another within the limits of 10^{-6} to 10^{-7} A. It may be considered an established fact that the basic cause of dark current in an multiplier is the thermionic emission which can be considerably decreased by increasing the operating output or by cooling the cathode (8,9).

The magnitudes of the spectrosensitivity and the dark current, as is well known, determine the threshold sensitivity of the multiplier. (The term threshold sensitivity means the point at which the light stream produces a flux equal to the dark current. In fact, the threshold sensitivity is determined by fluctuations of the dark current.) In striving to improve the parameters of a photoelectron multiplier, i. e., to lower its threshold sensitivity, an antimony-cesium cathode was substituted for the Ag-O-Cs cathode. Among the qualities of the antimony-cesium cathode are a high spectrosensitivity in the visible part of the spectrum (10,11), large quantum output (12,13), and resistance to changes of temperature, as well as a low value of dark current (14), and high durability. There is no apparent possibility of combining a Cu-S-Cs emitter and an antimony-cesium cathode since, according to literature on this subject, the presence of traces of sulfur greatly lowers the sensitivity of the latter (15).

However, as a result of the work undertaken, as may be seen below, a technological method was worked out which guaranteed the production of a sensitive cathode with a Cu-S-Cs emitter containing sulfur.

Research Procedure

The procedure in obtaining secondary-electron multipliers (having an antimony-cesium cathode) with a glass envelope consisted mainly of the following stages:

1. Application, by chemical cooling and electrolysis, of a layer of silver on the inner wall of a glass tube. The silver layer served as a lining for the Cu-S-Cs emitter and made contact with 15 platinum lead-ins soldered into the glass. As a result of the deoxidizing reaction, the silver was separated into:

$$2[Ag(NH_3)_2]OH + C_6H_{12}O_6 = C_6H_{12}O_7 + 4NH_3 + H_2O + 2Ag.$$

2. Electrolytic application of a layer of copper and treatment with hydrogen sulfide. Due to the action of the sulfur, a layer of cuprous sulfide was formed on the copper. The reaction, as is well known, takes place in two ways:

$$Cu_2O + H_2S = Cu_2S + H_2O,$$
$$2Cu + H_2S + \tfrac{1}{2}O_2 = Cu_2S + H_2O.$$

3. Sealing the antimony atomizer in the tube and degassing the tube in a vacuum apparatus under conditions similar to the well-known method of preparing a layer of photoelement on glass.

4. Application of a local layer of antimony to the glass near the first stage by vaporization of an antimony ball, screened from the window-side of the multiplier, in a high vacuum (10^{-6} mm). The opaque layer of antimony produced in this manner has a metallic luster. To obtain simple antimony-cesium cathodes, the surface of the glass is cooled by an air current during the process of coating with antimony.

Activating Procedure

The layers (of antimony and cuprous sulfide) are activated at a temperature of 210° C with cesium vapor which is introduced through a glass bulb connected at the anode side of the tube. The cesium is obtained by heating a nickel sack filled with a mixture of CsCl+Ca in a high-frequency oven. The activating process is controlled by taking periodic measurements using a "guard ring," of the cathode photocurrent and "leaks" (interstage conductivity) between the cathode and the first stage. The source of light is provided by an incandescent lamp (6 - 8 volts) fastened to the cathode of the tube, which is excited only at the moment when measurements of the photocurrent are made.

The properties of the inspected cathode changes according to the degree of the absorption of the cesium by the antimony layer. This is evident in the changes of the photocurrent and thermoelectric current in time. When the point of maximum sensitivity is reached, the layer takes on a dark red color as the light is passed through, during which the photoemission remains for some time at a constant maximum magnitude. At this point the oven is switched off, the bulb with the excess cesium unsoldered and, if there are no large "leaks" in the last stages, the secondary-electron multiplier is unsoldered.

The thermal emission of the antimony-cesium cathode at this temperature (210°C) is small, approximately 60 - 80 times less than for an cesium-oxide cathode. For this reason, in contrast with the cesium-oxide cathode, where thermal emission at the given temperature is sufficiently large, we were obliged, in obtaining antimony-cesium cathodes, to control the activating process from the standpoint of photocurrent and not thermoelectric emission.

The well-known fact (16) of the dependence of photosensitivity on the temperature of an antimony-cesium cathode demanded attention. The photosensitivity of the cathode increased in proportion to its cooling from 210° C to room temperature. At room temperature the photosensitivity was two to three times greater than at 210° C.

One very interesting result was that at a given temperature, the copper-sulfide layer in the cascades was also activated by the secondary-electron emission simultaneously with the activation of the cathode. This condition, and also the absence of an intermediate stage of oxidation and partial deoxidation, simplified the technological method of obtaining a photoelectron multiplier in which the Ag-O-Cs cathode in it is replaced by antimony-cesium cathode which surpasses the Ag-O-Cs only in respect to sensitivity in the red and infrared bands of the spectrum. Multipliers with an antimony-cesium cathode, obtained by the method mentioned, were investigated from the standpoint of the photoelectric properties of the cathode and the secondary-electron emission properties of the emitters in cascade.

Photosensitivity of the Cathode

Measurement of the absolute photosensitivity is carried out by illuminating a point (1 sq cm) on the surface of the cathode by undecomposed light (2.6×10^{-2} lm) from an incandescent lamp with T_c = 2,848° K. As shown by Table 1, the photosensitivity of the cathode in multipliers varies between the limits of 50 and 125 μA/lm. According to Glover and Janes (17), the photosensitivity of an antimony-cesium cathode to daylight is approximately two - two and one-half times greater than the photosensitivity to the light of an incandescent lamp with T_c = 2,848° K.

Table 1

No of Multipliers (test series)	Sensitivity of Cathode (in μA/lm)
1	50
2	125
3	68
4	103
5	92
6	62
7	112
8	68
9	68
10	101

The photosensitivity of an antimony-cesium photocathode, as is well known, can be greatly increased by surface oxidation with oxygen gas at low pressure (13,15), which can be done in practice without much difficulty. It is sufficient to state that MELZ, using this method in serial production obtained antimony-cesium photoelements with a sensitivity of 125 μA/lm or better.

However, the spectrosensitivity curve of highly sensitive photoelements differs from that of standard antimony-cesium photoelements; the maximum of sensitivity and the red limit are displaced toward the long-wave lengths, which results, as may be seen from Sommer's work (13), from the decrease in the operating efficiency due to the oxidation of absorbed cesium atoms.

This is also confirmed by the increase in thermionic emission. For this reason we were obliged, for the time being, to give up the idea of increasing the sensitivity, because, otherwise, the gain of two or more times in the spectrosensitivity would entail, as will be evident later, the increase in the photoelectron multiplier of the dark current which in effect is thermo-emission. [illegible] we did not know how oxidation would affect the secondary-electron properties of Cu-S-Cs emitters in cascade.

Secondary-Electron Emission of a Cu-S-Cs Layer

With a view to clarifying the secondary-electron properties of the emitter in a photoelectronic multiplier, measurements of the coefficients of secondary-electron emission σ of a Cu-S-Cs layer in all stages were made by a simple method. The essence of the method consisted in taking simultaneous measurement of three adjacent stages which were placed under voltage. The initial electrons were photoelectrons, originating as a result of illuminating one of the cascades by a narrow pencil of white light (sensitivity of the Cu-S-Cs layer 2 - 4 μA/lm).

For this purpose, in the process of plotting the curve of the emitter, an aperture 2 mm wide is left along the whole length. Photoelectrons, moving in an electric field, are focused by an external magnetic field onto the neighboring stage whose coefficient of secondary-electron emission is under examination. The secondary electrons, as they fly out, are collected on the third stage.

The circuit used in the measurements is given in Figure 1. By connecting a highly sensitive mirror galvanometer alternately in positions A and B, measurements are made of the photocurrent I_ϕ and the corresponding difference between the secondary electron I_B and the photocurrent. The quantity $I_B - I_\phi$ is a function of the magnetic field (at a constant interstage voltage). This relationship is transferred to a curve (Figure 2), on which there is a rectilinear area corresponding to the maximum value of $I_B - I_\phi$. The steady

maximum values of $I_B - I_\phi$ at magnetic fields ranging from H-105 to H-120, is probably due to the complete focusing of all photoelements flying out of the illuminated surface to the neighboring stage whose coefficient of secondary-electron emission is of interest to us. In measuring photocurrent and $I_B - I_\phi$, the light intensity from the incandescent lamp is kept constant at 2.6×10^{-2} lm.

If we assume that this proposition corresponds with the facts, the coefficient of secondary-electron emission may be expressed by

$$\sigma = \frac{(I_B - I_\phi) + I_\phi}{I_\phi}$$

The measured σ of two photoelectron multipliers with an antimony-cesium cathode are given in Table 2. As may be seen from the table, the coefficient of secondary-electron emission, on an average, for a Cu-S-Cs emitter during a 70-volt velocity of the initial electrons equals 3 - 3.5. If we assume that a partial diffusion of the photoelectrons takes place during such a method of measurement, our emitter will be characterized by still higher coefficients of secondary-electron emission. The method employed for secondary electron measurements, although differing from the usual method, is better adapted to the conditions obtaining in the utilization of the phenomenon of secondary-electron emission to amplify the photocurrent of the cathode in a Kubetskiy-type multiplier.

Table 2

Amplifier No 1/3		Amplifier No 37	Amplifier No 37
Amplifier Stages	σ 50	Amplifier Stages	σ 50
I	3.25	I	2.5
II	4.0	II	3.0
III	3.9	III	2.8
IV	4.1	IV	2.85
V	3.5	V	2.85
VI	3.75	VI	2.9
VII	4.1	VII	2.85
VIII	4.1	VIII	2.8
IX	2.0	IX	2.95
X	4.1	X	2.85
XI	3.8	XI	2.85
XII	3.4	XII	3.0
XIII	3.3	XIII	3.05

The coefficient of secondary-electron emission, as is well known, is a function of the velocity of the initial electrons (in our case, the interstage voltage). This dependence of the Cu-S-Cs emitter on voltage is shown in Figure 3. σ is computed by the above-mentioned formula for the calculation of changes in I_ϕ in relation to voltage and, at the same illumination (voltage-current characteristic).

The use in a photoelectron multiplier of an effective emitter designed for 13 electrically insulated stages (resistance of interstage glass spacing being 5×10^9 to 5×10^{10} Ω) at a total of 1,000 volts provides 5 to 6 $\times 10^5$ times greater intensification of the cathode photocurrent. The spectro-sensitivity at the given voltage reaches 30 - 45 A/lm [sic]. The source

of light in determining the spectrosensitivity is also provided by an incandescent lamp (T_c = 2,848°K). In daylight, due to the peculiarity of the spectral characteristic of the cathode, the spectrosensitivity of the amplifier will also be several times greater.

Spectral Sensitivity

Unlike the cesium-oxide cathode, the ordinary antimony-cesium cathode possesses great sensitivity in the visible part of the spectrum.

In the spectrum laboratory of the Institute of Physics imeni P. N. Lebedev, the spectrosensitivity curve, represented in Figure 4, was taken for one of the types of photoelectron multipliers. The maximum lies in the region of λ = 4,530 Å, which corresponds with the data of Gorlich (10). The red limit lies in the region of λ = 6,350 Å.

The spectrosensitivity of a photoelectron multiplier in the long-wave range, below 4,000 Å, was not measured because of the strong absorption of the light by the glass envelope of the multiplier. However, there was data (18) on the considerable sensitivity of antimony-cesium photoelements in the range close to ultraviolet also. The photoelectron multipliers described may be utilized not only to measure visible light but also, by means of fluorescent screen, to measure the intensity of ultraviolet light.

Figures 5 and 6 give a comparison of the curves of spectrosensitivity, obtained by Rodionov (19), of two Kubetskiy photoelectron multipliers with a cesium-oxide cathode, having different dark current values. In the two examples shown, the large dark currents, the maximum sensitivity in the red area, and the red boundary are displaced toward the long-wave lengths.

Dark Current of the Amplifier

One of the important parameters determining the threshold sensitivity of a photoelectron multiplier is its dark current (more exactly, its fluctuation). As a result of substituting an antimony-cesium cathode for a cesium-oxide cathode, the dark current of a multiplier with guard ring and a total voltage supply of 750 - 1,000 volts, decreases two or three times on an average (Table 3). The dark current of the cathode, intensified by the phenomenon of secondary-electron emission, is a thermoelectric current of the cathode and emitter at the first stages.

As may be seen from the work of Rodionov (10), the magnitude of the dark current of a multiplier with an antimony-cesium cathode determines the position of the red limit in the spectral properties of the cathode. For a copper-sulfide-cesium emitter, the red limit lies in the region of λ = 11,000 Å (20); compared with that for an antimony-cesium cathode, it has been displaced toward the longer waves. Hence, by analogy it may be stated beforehand that thermal emission with a Cu-S-Cs emitter is greater than with an antimony-cesium cathode. The thermal emission of an antimony-cesium cathode, according to the preliminary data of Glover and Janes (17), at room temperature, equals 10^{-13} to 10^{-14} A/sq cm. If it be assumed that these thermoemission values correspond to the facts, the multipliers developed (with average sensitivity) with an amplification of 10^5 (not counting the thermoemission of the emitter at the first stages) should have dark current of at least 3×10^{-8} to 3×10^{-9} A. The area of the cathode is equal to 3 sq cm. In reality, the dark current in some multipliers with an antimony-cesium cathode has a value of 4.5×10^{-10} A or even less.

Table 3

(A large number of the amplifiers shown here are already in use in various scientific-research organizations.)

No of Amplifier	Dark Current at Room Temperature (18°C) (A)	Total Amplification	Total Supply
E/2	1.3×10^{-8}	1×10^5	750
E/5	5.4×10^{-9}	5×10^5	1,000
E/6	2.7×10^{-9}	1×10^5	750
E/8	2.7×10^{-9}	1×10^5	750
E/359-1	$< 4.5 \times 10^{-10}$	1.5×10^5	1,000
E/245	$< 4.5 \times 10^{-10}$	1×10^5	1,000
E/267	2×10^{-9}	1×10^5	1,000
E/268	6×10^{-10}	1×10^5	1,000
E/269	5.4×10^{-9}	1×10^5	750
E/29	2.7×10^{-9}	2×10^5	1,000
E/33	4.5×10^{-10}	1×10^5	1,000

In our opinion, the small dark current values (4.5×10^{-10}A) in various amplifiers probably explain the unfavorable conditions for full intensification of the thermoemission of the cathode of the emitter in the first stages. Indeed, the position of the permanent magnet and the intensity of the magnetic field are selected when assembling the amplifiers in order to provide the greatest spectrosensitivity when only a part of the cathode is illuminated (usual operating conditions). The source of the electrons which, generally speaking, can be considerably intensified due to secondary emission, is the entire surface of the cathode and emitter at the first stage.

Hence, substitution of an antimony-cesium cathode for a cesium-oxide cathode in an amplifier on the one hand, and, probably, the different paths of the curves of the interval sensitivity and the dark current dependent on the magnetic field on the other hand, will permit improvement of the multiplier having a very small dark current. For comparison, we give the values of dark currents (at a voltage of 1,100 -1,250 volts) of American multipliers (4) with an amplification of $\sim 2 \times 10^5$ in Table 4. (As shown by Kron's work (5), the multiplier 1P21 with an antimony-cesium cathode has an amplification of $\sim 10^5$, a dark current of 2×10^{-9}A.) As may be seen from this table, our multipliers, on an average, are superior in regard to dark currents. In regard to spectrosensitivity at the indicated voltage, our multipliers with antimony-cesium cathodes have a considerably greater value than the RAC 931, because of the great sensitivity of the cathode and great amplification (especially at 1,250 volts). The spectrosensitivity of an RCA 931 amplifier at 1,250 volts equals 2.3 A/lm (2).

To measure any feeble light flux, it is desirable to have multipliers with still smaller dark currents. One of the methods of reducing the dark current of the multiplier (to some extent) consists of cooling the cathode.

Table 4

Type of Multiplier Phototube	Dark Current (at 108 V in Series) at Room Temperature (18° C)
RCA 1P21 No 44 -- 6162	1.3×10^{-9} A
RCA 1P21 No 34 -- 5168	1.4×10^{-8} A
RCA 1P21 No 44 -- 5492	2.8×10^{-8} A
RCA (no number)	1.4×10^{-8} A
RCA 931 No 594	1.4×10^{-8} A

A method for cooling the cathode has already been employed in some research work (8,9), in which amplifiers with cesium-oxide cathodes were used. It is impossible to tell beforehand whether cooling the cathode will be more effective in reducing the dark current in a multiplier with an antimony-cesium cathode, as the dark current depends not only on the thermoemission of the cathode, but also on the emitter at the first stage. Clarifying this question is obviously a problem (6). In experiments in cooling the antimony-cesium cathode of a multiplier, it is necessary to take into account the experimentally established fact (16), of the reduction of its photosensitivity (according to linear law) in proportion to its cooling below 0° C, depending on the sharp increase of cascade resistance.

This phenomenon does not occur in the application of an antimony layer on the metal lining. Therefore, the application of a layer of antimony on the metal lining also is an obvious problem in perfecting photoelectron multipliers. The first effort in this direction was not successful since, in the technological method employed, the metal lining (silver) increased the dark current of the multiplier. This increase, apparently, was the result of contamination of the lining (not excluding the possibility of the formation of a fusion or amalgam of the antimony with the silver) in the process of constructing the multiplier according to the present method.

A general view of a 13-stage photoelectron multiplier mounted on a Kubetskiy-type base suitable for cooling a cathode is shown in Figure 7 /photograph, not reproduced, but available in original document at CIA/.

"Leaks" Through Glass

Application of a silver-layer emitter on glass, as has been already pointed out, is a distinctive peculiarity of a photoelectron multiplier. It has been established that the antimony absorbed by these spacings to a great degree conditions the above-mentioned resistance values. Where a cesium-oxide layer is employed as an emitter in the stages, the resistance diminishes in time because of the transference of the cesium (lateral diffusion) from the emitter to the glass.

At present, in photoelectron multipliers with Cu-S-Cs emitters, the resistance remains constant, that is, the above-mentioned phenomenon does not take place. Nevertheless, the resistance of the spacing between the last stage and the anode is not large enough to limit the possibility of measuring very feeble light fluxes. Thus, for instance, in case of resistance equalling 4.5×10^{9} Ω (the lower limit) at a voltage of 50 volts,

the leakage through the glass onto the anode is approximately 1 x 10^{-8} A, that is, greater and, in some cases, commensurate with the value of the dark current (multiplied thermionic current) of the photoelectron multiplier.

This circumstance forced us to introduce a cooling ring, representing a narrow stage, the area of which was very small in comparison with the anode, and to increase the width of the glass spacing between the cooling ring and the anode. This led to an increase in resistance. The introduction of this cooling ring (an additional stage with an applied potential equal to the potential of the anode) does not afford measurements for losses in secondary electrons within the limits of error; that is, the reduction of spectrosensitivity; it simply eliminates the leaks through the glass between the last stage and the anode. (In measuring very feeble light streams the procedure is to use supplementary tube amplifiers with a large input (grid) resistance. In such cases introducing a cooling ring into the multiplier does not solve the problem. Hence, the next question is the problem of increasing the glass spacing when constructing multipliers with a sealed-in anode.)

The solution of the problem of the combination of an antimony-cesium cathode with a copper-sulfide-cesium emitter permits a great improvement in the parameter of a photoelectron multiplier, that is, in the construction of a highly sensitive apparatus required to measure a feeble light flux. At present, there are 15 such photoelectron multipliers in use in various scientific-research organizations. Thus, for example, they are being used at the Institute of Physics imeni P. N. Lebedev for experiments in photometry on weak spectrum lines, and for the study of phenomena of luminescence (23) and of polarization of light. (Some results obtained by a special analysis laboratory for the use of photoelectron multipliers with antimony-cesium cathodes were reported in December 1946 at the Conference on Spectrum Analysis (24).

Beside the qualities of multipliers mentioned above, another important advantage in working with them previously taken up in Rodionov's article (19) is their freedom from interference; that is to say, the multipliers do not need to be shielded from electrostatic or electromagnetic interference. The performance of the multiplier is not altered by the use of a high-power spark discharger as a source of light, located a short distance from it.

Low-Voltage Amplifiers

Our standard photoelectron multipliers designed for operation at 750 - 1,000 volts cannot be employed (without altering the apparatus) in talking pictures because of the low-power output and high-supply voltage. In talking pictures, as everyone knows, the current of the photoelement is intensified by the employment of exciting lamp systems. As the lamp systems are the main source of sounds, the obvious solution, formulated at the All-Union Conference on Cathode Phenomena in a Vacuum and in Discharged Gases (22), is the replacement of various vacuum-tube amplifying stages by small, cascade low-voltage multipliers with antimony-cesium cathodes. We have already obtained some types of such multipliers. At 350 volts, their spectrosensitivity is equal to 5 - 10 mA/lm. A simple calculation shows that the interval sensitivity of such multipliers may be increased by greater precision in technology, which is the next step in the present work.

A photograph of a low-voltage multiplier with a socket base is shown in Figure 8 [not reproduced but available in original document at CIA].

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In conclusion, I consider it my duty to express my gratitude to Academician A. A. Lebedev and to L. A. Kubetskiy, Candidate in Technical Sciences, for their valuable advice and constant interest in this work, and also to Technician M. D. Gritskevich for technical aid in mounting the multipliers on a base.

Conclusions

1. An explanation has been given of the possibility of combining an antimony-cesium cathode and a copper-sulfide-cesium emitter on a glass layer in a photoelectron multiplier.

2. A method has been worked out for obtaining multipliers with a high degree of sensitivity in the visible region of the spectrum, with low dark currents (on an average one half to one third of that of multipliers with cesium-oxide cathodes).

3. An analysis has been made of the photoelectric properties of a cathode and of the secondary-electron properties of an emitter in the multiplier stages.

4. Samples have been made of small cascade (low-voltage -- 350 volts) multipliers with an antimony-cesium cathode, having a total amplification of 2×10^6.

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[Appended figures follow.]

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Figure 1

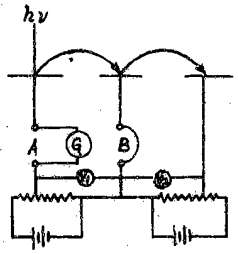

Figure 2

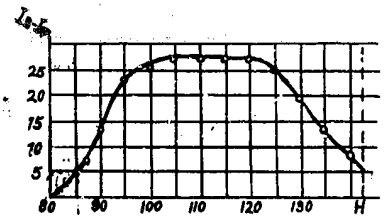

Figure 3

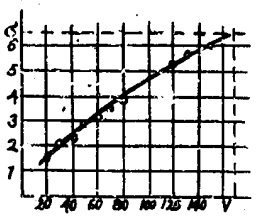

Figure 4

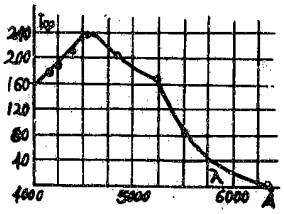

Figure 5

Figure 6

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